A fast pipelined multi-mode DES architecture operating in IP representation

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A Fast Pipelined Multi-Modes DES Co-Processor Operating in IP Representation

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Abstract

The Data Encryption Standard (DES) is a cipher that is still used in a broad range of applications, from smartcards, where it is often implemented as a tamper-resistant embedded co-processor, to PCs, where it is implemented in software (for instance to compute `crypt(3)` on UNIX platforms.) To the authors' knowledge, implementations of DES published so far are based on the straightforward application of the NIST standard. This article describes an innovative architecture that features a speed increase for both hardware and software implementations, compared to the state-of-the-art. For example, the proposed architecture, at constant size, is about twice as fast as the state-of-the-art for 3DES-CBC. The first contribution of this article is an hardware architecture that minimizes the computation time overhead caused by key and message loading. The second contribution is an optimal chaining of computations, typically required when "operation modes" are used. The optimization is made possible by a novel computation paradigm, called "IP representation".

1. Introduction

The Data Encyption Standard, DES, is a block product cipher algorithm promoted by the NIST. The latest version of the standard is known as FIPS 46-3 [16], and includes the definition of "triple DES". The "DES modes of operation", standardized in FIPS 81 [14], is a companion document devoted to the description of the secure use of DES when the messages to encrypt are longer than 8 bytes.

Since its inception, DES has been used pervasively by many applications that require data confidentiality. Since 2001, DES has been superseded by the Advanced Encryption Standard AES [17]. However, in practice, a lot of hardware or software applications still resort to DES.

The DES algorithm turns a 64-bit confidential data block, nicknamed *plaintext*, into another 64-bit data block, nicknamed *ciphertext*, using a standardized bijection parametrized by a 56-bit secret, nicknamed *key*. The bijection DES_k is crafted in such a way it is almost impossible to retrieve the plaintext from the ciphertext without the knowledge of the key k. The bijection can be inverted: this operation is called *decipherment* and noted DES_k^{-1}. When it is not relevant whether the algorithm performs encipherment or decipherment, the neologism "*cipherment*" is employed instead.

Several attacks against the plain DES version were published. They can basically be classified into two categories: *algorithmical* and *physical* attacks.

Algorithmical attacks are also referred to as cryptanalysis [2, 13]. Those analyzes are somehow unrealistic, since a large amount of {plaintext, ciphertext} couples must be intercepted. The exhaustive search of the key [5] has been *publicly* feasibly since 1977, as proved by the RSA Laboratory's "DES Challenge II" being won in 1997 in 39 days by a network of computers running the distributed application DESCHALL and in 1998 in 3 days by a dedicated machine built by the EFF. Other methods to speed-up the search using pre-computated datasets have been put forward [9].

To counteract those attacks, variants of the DES were proposed. We list below three of the most widespread ones:

1. **Modes of operation** allow a message consisting of several 64-bit blocks to be ciphered in chain. The idea is that the knowledge of each of the 64-bit ciphertext blocks actually depends on the corresponding plaintext block, also of some, if not all, of the previous ones, and of an initialization vector (IV). The standardized modes of operation are ECB, CBC, CFB and OFB [14]. ECB and CBC are *block-ciphers*, whereas CFB and OFB are *stream-ciphers*. The latter two are actually defined in the K-bit version, $1 \leq K \leq 64$. As the $K = 64$ version is the most efficient in terms of

throughput, it is usually the sole version to be implemented (refer for instance to `openssl` [6].) Because of the "short cycle property", NIST explicitly does not support $K < 64$ for OFB [15, *page* 13].

2. **TDEA (informally called "triple-DES" or "3DES")** is described in the annex of the DES standard [16, *page* 22]. Three 64-bit keys $k_i, i \in \{0, 1, 2\}$ are used instead of one. The encipherment consists in computing $\text{DES}_{k_2} \circ \text{DES}_{k_1}^{-1} \circ \text{DES}_{k_0}$ whereas decipherment is $\text{DES}_{k_0}^{-1} \circ \text{DES}_{k_1} \circ \text{DES}_{k_2}^{-1}$. Triple DES is customarily used with two keys [18] ($k_0 = k_2$.) Notice that when the three keys are taken equal, $k_0 = k_1 = k_2$, triple DES actually computes plain DES, which guarantees the backward compatibility of 3DES engines.

3. **DESX [10]** is a data whitening technique, proposed by Ron Rivest from RSA Labs. It consists in adding two 64-bit blocks, `in_white` and `out_white`, to the key. The key `in_white` is used to *exclusive-or* (*i.e.* `XOR`) the plaintext prior to starting DES and `out_white` to `XOR` the result after the cipherment.

Those variants can of course be combined at will. For instance, triple-DES using two keys in CBC mode is often used to encipher long messages.

Physical attacks are the most recent threats against DES and its variants. The side-channel attacks, such as DPA [11] or EMA [7], allow to retrieve the keys by the analysis of the physical emanation of the device while it is handling the key. Partial side-channel information, such as the Hamming weight of key chunks or key-dependent correlations between two small chunks of data, suffice to recover the full key, provided enough measurements can be performed. The faults injection attacks [3] consist in either perturbing transiently the circuit or to damage it to enhance other attacks. Algorithmical counter-measures (modes of operation, 3DES or DESX) do not protect against physical attacks. Both side-channel and fault attacks can be thwarted, with more or less success, by using leakage-proof logic and adequate sensors, for instance.

In this paper, we describe an architecture able to compute DES and its variants efficiently. More precisely, the described architecture can compute: DES in ECB, CBC, 64-bit CFB and 64-bit OFB, as well with simple or triple DES using two keys. The cryptanalytic strength of the variant as well as the security of its implementation against physical attacks is out of the scope of this paper.

The rest of the article is organized as follows. Section 2 discusses the DES datapath optimization: an hardware pipelined architecture is presented. Section 3 applies to both software (SW) and hardware (HW) implementations. It introduces the so-called "IP representation" computational framework, which allows to optimally chain DES computations. In Sec. 4, the gain of proposed architecture over state-of-the-art architectures is discussed. Finally, Sec. 5 summarizes the paper.

2. DES Datapath Improvement thanks to a Generalized Pipelining

In the DES algorithm, the control is independent of the data. It is thus safe to consider the design of the datapath and the control finite state machine (FSM) as two distinct tasks. This section is devoted to the datapath. The control is further studied in Sec. 3.

2.1. Straightforward DES

The inputs of the DES algorithm are two 64-bit blocks, the plaintext and the key. The two operands cannot be loaded in DES operator in one go, since data provided by processors are typically on $n = 8$, 16 or 32 bits. In the rest of the article, we assume that the DES co-processor is fed by an $n = 8$-bit wide data bus. This figure corresponds to the case of an embedded system built around a microcontroller.

Most of DES implementations elude the question of the connexion to an $n < 64$ wide bus [8, 20, 4]. Other implementations, such as [1], do not take advantage of the architectures presented in this paper.

The knowledge of the DES algorithm internals is not required to explain the rationale of the three implementations discussed in this paper. Only the following facts are indeed relevant for the coming analysis:

- DES is a Feistel cipher, which means that the message is divided into two halves (L and R), among which only L undergoes a logical operation dependent on the some bits of the round key, R being left untouched. Then the two halves are swapped, and the process is iterated sixteen times. After the last round, L and R are not swapped.

- Before any processing, the message bits are shuffled, using a permutation called IP. At the end of the Feistel scheme, the message is de-shuffled by the inverse permutation $\text{FP} \doteq \text{IP}^{-1}$.

- Only 56 bits of the key are used. As justified in the standard [16, *page* 1], every byte of the key has a parity bit, chosen so that the Hamming weight of every byte of the key is odd. In a similar way to the message, the key bits are initially shuffled, using the permutation PC_1. The key is modified at each round, by a transformation known as "key schedule", consisting in one or

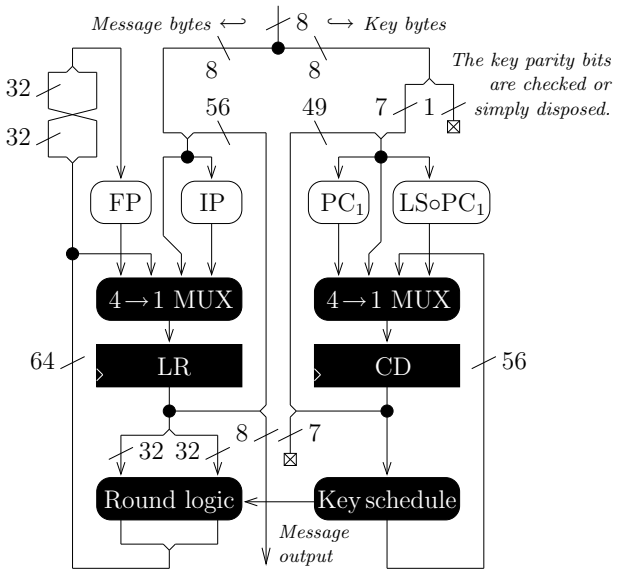

Figure 1. Straightforward architecture for a DES module, equipped with demultiplexing logic to load the message and the key one byte at the time.

two Left Shifts, LS (resp. Right Shifts, RS) for encipherments (resp. decipherments), followed by a permutation called PC_2. The shifts are designed in such a way that CD is back to its initial value after a full encipherment. They are implemented by a 2×2 input multiplexor ($4 \rightarrow 1$ MUX.) However, when enciphering, the initial value to be presented at PC_2 is LS(k), whereas when deciphering, bare $\mathtt{Id}(k) \doteq k$ is to be used instead. Given that a "*general purpose*" DES module is designed to both encipher and decipher, both PC_1 and LS $\circ$ PC_1 must be computed in parallel.

As a result, a straightforward implementation of DES requires the following sequential resources:

1. one 64-bit register (named LR in [16, *page* 11]) to hold the ciphertext and to store the 16 intermediate messages, and
2. one 56-bit register (named CD in [16, *page* 19]) to hold the key stripped off its parity bits and to store the 16 round keys.

Without any additional registers, the storage of the plaintext in LR and of the key in CD requires a demultiplexing logic, illustrated in Fig. 1. For the sake of clarity, the control part has been omitted in Fig. 1: the multiplexors and the key schedule logic are *implicitly* commanded externally.

The schematics follow those conventions:

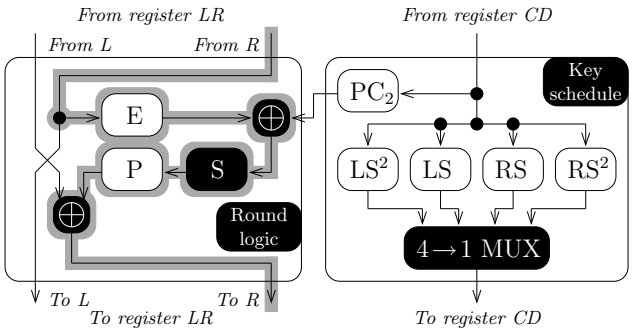

Figure 2. DES round and key schedule combinatorial logic. The critical path LR → Round Logic → LR is highlighted.

Table 1. Resources area [μm^2] in Fig. 1, synthesized at 400 MHz in a 130 nm ASIC low-leakage technology.

Datapath				Control
Round logic	Rest: Dataflow logic			
S + XOR	Permutation	MUX	DFF	FSM
8482	0	7193	3437	5075

- sequential gates, Flip-Flops (DFF) in our case, are represented as boxes (▮),
- combinatorial gates are represented as boxes with round corners (▢ or ■),
- permutation-only gates, such as IP or buses merge (⋎) or split (⋏), are hollow, whereas
- gates made up of logic have a solid background ;
- datapath forks are represented with solder dots (•) and
- when some bits are useless, they are disposed (⊠).

The entire DES design is made up of bit shuffling dataflow primitives (permutations, multiplexors and flip-flops), with the exception of the round logic. This fact is depicted on Fig. 2, where the critical path of the datapath is highlighted. The typical resource utilization in the straightforward architecture of Fig. 1 is illustrated in Tab. 1.

Registers LR and CD must be loaded sequentially. In a pipelined architecture, the use of "enable" signals on the DFF can usually be avoided. It is possible to use none, if the key is loaded first into CD, because there is a way to keep it "apparently" still. As $LS^2 = LS \circ LS$, $RS^2 = RS \circ RS$ and $LS \circ RS = RS \circ LS = \mathtt{Id}$, it is easy to control the key in

such a way it is unchanged before and after the LR loading. We assume that the transformation is $LS^4 \circ RS^4$, and in the rest of the paper. As for LR, it never has to maintain its state more than one clock cycle. The same remark will hold for the refinements carried out on this straightforward architecture, because they are "pipelined": data (other than the key) flows continuously through the datapath, without having to wait at any time.

The straightforward pipeline is thus initially busy during $64/n = 8$ clock cycles to load the key into CD. During another eight clock cycles, the key is applied $LS^4 \circ RS^4$, whilst the first message block is loaded into LR. Then the DES engine can start the sixteen iterations. The next eight clock cycles are devoted to flushing the result out.

In the straightforward scheme of Fig. 1, every computation has an overhead in execution time due to data loading / unloading in the LR or in the CD register. The evaluation of the architecture throughput does not take into account the key loading, because most applications use only one key, loaded once for many consecutive cipherments (the case of 3DES is detailed later in Sec. 3.2.) The loading stage consumes $64/n = 8$ cycles, and monopolizes the LR or the CD registers, so that it is impossible to parallelize a loading with a DES cipherment (16 cycles). Then the message must be output, which requires another $64/n = 8$ cycles. Notice that for read and write accesses to be done in parallel, two RAMs must be connected to the DES engine. In terms of memory usage, it is however optimal to use a single RAM, since every computation result can be written over the original message. Thus, the maximum throughput is one encipherment per 8+16+8 clock cycles (2.0 bit/clock).

The straightforward architecture suffers two drawbacks, that impede the cryptoprocessor performances:

1. The DES cannot perform cipherements whilst new blocks m_{i+1} are read and processed blocks DES(m_i) are written out.

2. The LR register is preceded by multiplexors, that increase the critical path.

The next section describes and motivates a novel pipelining scheme, where the data can be both input and output byte by byte, in parallel with DES cipherments.

2.2. DES Datapath Fast Pipelining

The drawbacks put forward in the previous section can be overcome by a more elaborate pipelining scheme of the DES cryptoprocessor. The principle is to parallelize the message inputs and outputs with the DES algorithm. A comparison between the so-called *iterative* and *pipeline* architectures of DES inner-loop is discussed in [19, *page* 589]. The difference is that an iterative DES engine

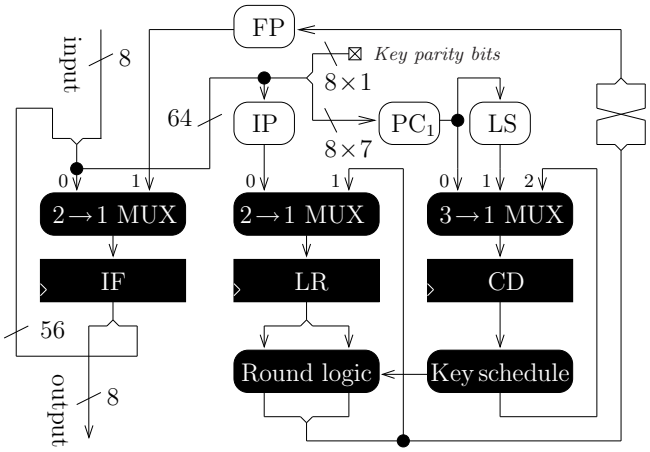

Figure 3. Proposed pipelined DES 8-bit datapath for ECB cipherments.

processes one cipherment at the time, whereas a pipeline DES engine can process many – up to 16 – at the same time. In all the architectures presented in this paper, DES is computed iteratively. However, the outside view of the DES engine is more like a pipeline: data is not input and output monolithically, but rather byte by byte. It must be clear that, throughout this paper, the term "pipeline" refers to the way the data is loaded and unloaded.

A 64-bit register, called IF (because of its role of Inter-Face between the 8-bit inputs and the 64-bit blocks involved within DES), is added to the DES cryptoprocessor.

IF is designed to have two possible sources: it can input either individual bytes or 64-bit blocks. In the first case, the output of IF is shift by 8-bits to make room for the incoming byte, to be concatenated with the others already collected. The byte that has been "shift-out" is not lost: it is available at the eight-bit output of the pipeline. In the second case, a 64-bit block, such as the result of the DES computation, is latched into IF, in a view to being output byte by byte. In the meantime, the whole content of IF can be transferred to LR, so that the DES datapath is ready to follow up on another cipherment.

In fact, the same IF register can be reused to manage the 8-bit $\leftrightarrow$ 64-bit conversion for both LR and CD. Figure 3 illustrates that the pipeline is generalized to cover both the round logic and the key schedule.

A more detailed description of the pipelined process is given below and illustrated in Fig. 4 for DES-ECB encipherment with one key:

1–7: During seven clock periods, the seven first bytes of the key k are loaded, side-by-side, into IF.

8: The blocks comprised into the last byte of the key

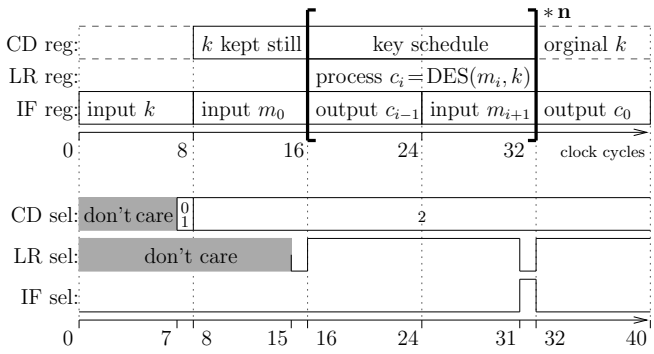

Figure 4. Pipeline (cf. Fig. 3) steps involved in ECB cipherments $i = 0, 1, \cdots, n-1$**.** *Upper part***: registers content (**c_{-1} = '-' **is don't care).** *Lower part***: multiplexors selection signals.**

$k[56, 63]$, concatenated with the already loaded seven others $k[0, 7] \,||\, \cdots \,||\, k[48, 55]$, is then loaded into CD, using selection 0 (when deciphering) or selection 1 (when enciphering).

9–15: During the seven following clock periods, the message m_0 is built-up into IF.

16: The message m_0, now complete, is transferred into LR. In the meantime, k is kept still in CD, which is possible, as already shown in Sec. 2.1. Incidentally, the result $\mathrm{DES}_k(m_{-1})$ of the previous computation – if any – is latched into IF.

17–24: The next eight cycles would be devoted to the output of an hypothetical $c_{-1} \doteq \mathrm{DES}_k(m_{-1})$, byte by byte ($c_{-1}[8 \cdot i, 8 \cdot (i+1)[, i \in [0, 8[$), from IF. In the present case, c_{-1} is a "don't care" result. However, starting from clock cycle 33, relevant c_i, $i \geq 0$ will be delivered byte by byte from IF. Concomitantly, the first eight rounds of DES are executed.

25–31: Whilst DES rounds are computed, a new 64-bit block of data is loaded (as already seen at clock cycles 9–15.)

32: DES has finished the sixteen rounds. The result is latched into IF. Simultaneously, a new 64-bit block of data is loaded into LR.

33–40: While DES starts the second cipherment, IF outputs c_0. The scheduling scheme goes on, with a periodicity of 16 clock cycles.

In practice, the pipeline is connected to a scratch-pad RAM. The pipeline reads from (cycles 1–8, 9–16, 25–32) and writes to (cycles 17–24, 33–40) the RAM on disjoint time slots. Therefore, a simple-port RAM (the less expensive type of RAM) is perfectly suitable. The throughput of the DES pipelined operator is 64-bit per 16 clock periods (4.0 bit/clock). The input and output latencies are 8 cycles (as in Sec. 2.1, we ignore the key initial loading.)

By the same token, the pipelined architecture improves the datapath speed. In the straightforward implementation, the LR register has four different input sources:

1. the input byte concatenated with the previous register content shifted by 8 bits to build the plaintext up,
2. the same block, but passed through IP, to start the computation and
3. the end of the round data, reinjected into LR for the next round.
4. the same block, swapped and passed through FP.

As already shown in Fig. 1, a $4 \rightarrow 1$ multiplexor, to choose between those four sources, directly precedes LR.

In the pipelined architecture, IP is performed concomitantly with the collection of the plaintext constitutive bytes. In does not slow down the computation, because in a hardware implementation, IP requires no logic: it is a mere reordering of wires. Consequently, LR has only two possible inputs in the pipelined architecture ; the $4 \rightarrow 1$ multiplexor is replaced by a $2 \rightarrow 1$. This optimization is crucial, since this multiplexor is on the critical path (LR $\rightarrow$ Round Logic $\rightarrow$ LR).

3. Optimal SW/HW Partition to Realize all DES Variants

3.1. IP Representation

The notations used in this section are inspired from `openssl` [6] internals:

- `des_encrypt1` is the full DES,
- `des_encrypt2` $\doteq$ IP $\circ$ `des_encrypt1` $\circ$ FP is DES, without IP nor FP.

Functions `des_encrypt{1,2}`(m, k, enc) take three arguments: a message m, a key k and a Boolean enc, specifying whether to encrypt ($enc = 1$) or decrypt ($enc = 0$.)

For any function set $f_i : [0\!:\!63] \mapsto [0\!:\!63]$, the following property holds:

$$\Pi_i \left(\mathrm{FP} \circ f_i \circ \mathrm{IP}\right) = \mathrm{FP} \circ \left(\Pi_i f_i\right) \circ \mathrm{IP}\,, \qquad (1)$$

$$\text{where: } \Pi_{i=i_{\min}}^{i=i_{\max}} f_i \doteq f_{i_{\max}} \circ \cdots \circ f_{i_{\min}}\,,$$

because FP $\circ$ IP is the identity function.

This property allows the chaining of DES operations without caring for IP and FP permutations. The "IP representation" computational framework consists in using the `des_encrypt2` primitive instead of `des_encrypt1`, the IP (resp. FP) being called only once at the beginning (resp. at the end) of the computation. The Equation (1) can be applied to the following DES variants:

- $f_i = \texttt{des\_encrypt2}(m_i, k, enc)$ (ECB and ECB^{-1})
- $f_i = \texttt{des\_encrypt2}(m_i, enc?k_i{:}k_{2-i}, (enc{+}i)\%2)$, $\forall i \in \{0,1,2\}$ (triple-DES on one block m ; $m_0 = m$ and $m_{i+1} = f_i(m_i)$, the output being m_3)
- $f_i = \begin{cases} \texttt{des\_encrypt2}(m_i \oplus f_{i-1}, k, 1) \text{ if } enc = 1 \\ \texttt{des\_encrypt2}(m_i, k, 0) \oplus f_{i-1} \text{ if } enc = 0 \end{cases}$ (CBC and CBC^{-1}, with $f_{-1} = \text{IV}$)
- $f_i = \texttt{des\_encrypt2}(f_{i-1}, k, 1) \oplus m_i$, (64-CFB and 64-CFB^{-1}, with $f_{-1} = \text{IV}$)
- $f_i = \texttt{des\_encrypt2}(f_{i-1} \oplus m_{i-1}, k, 1) \oplus m_i$, (64-OFB and 64-OFB^{-1}, with $f_{-1} \oplus m_{-1} = \text{IV}$)

In software implementations, IP is not free as in hardware, because bits cannot be arbitrarily moved within or between words. In `openssl`, IP and FP are implemented using 32-bits registers in $5 \times (3\,\texttt{XOR} + 2\,\texttt{SHIFT} + 1\,\texttt{AND}) = 30$ operations.

DES `des_{en,de}crypt3` function performs triple DES on one block of plaintext. It is the only function from `openssl` that takes advantage of the optimization provided by the computation in the IP representation (1). All other functions, especially chained DES, are thus inefficient.

3.2. Multi-mode Pipelined DES Datapath Operating in "IP Representation"

The pipeline described in Sec. 2.2 (see Fig. 3) is not designed to chain cipherments. However, it can be enhanced to cope with triple-DES and all modes of operation. The rationale is to add two inputs to the multiplexer in front of LR:

1. the result of the previous DES, which allows triple-DES and also OFB (where the series $\left\{\text{DES}^i(\text{IV})\right\}_{i\geq 0}$ is computed),
2. *idem*, but `XOR`ed with the new message, which allows CBC and CFB chained modes.

The new inputs to LR are compatible provided they are in the IP representation. It basically means that inputs to DES must be previously IP'ed and that output of DES to be recycled must not be FP'ed. Additionally, the IF register must be able to latch the XOR between the new message and the current result, which is required by the stream modes (*i.e.* CFB and OFB) of DES. Those constraints lead to the versatile version of the pipelined DES datapath represented in Fig. 5. By default, the multiplexor in front of IF (resp. LR) selects the input 0 (resp. 1). At the end of every cipherment (*i.e.* every 16 clock periods), the multiplexers choose another input, as shown in Tab. 2.

The realization of triple DES requires a special schedule. The 3DES-ECB is illustrated in Fig. 6. The IF and CD registers sample their default inputs, selection 1 for IF and 0 for CD (corresponding to the ECB and ECB^{-1} lines in Tab. 2). The scheme for 3DES of Fig. 6 can be combined with the modes of operation. It suffices that the data to be output by IF and sampled into LR have non-default origins documented in Tab. 2 every 3×16 clock periods.

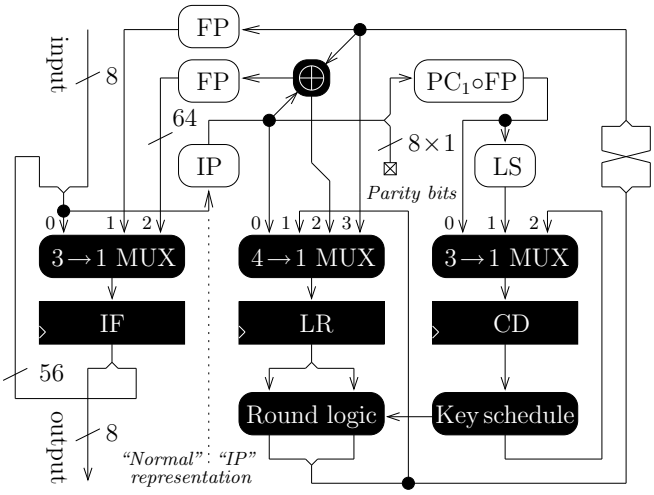

Figure 5. Proposed multi-modes pipelined DES datapath operating in "IP representation".

Table 2. Selected signals at the beginning of each DES chained with modes of operation.

Mode	IF MUX	LR MUX	Built upon
ECB	1	0	DES
ECB^{-1}	1	0	DES^{-1}
CBC	1	2	DES
CBC^{-1}	—	—	—
CFB	2	2	DES
CFB^{-1}	2	0	DES
OFB = OFB^{-1}	2	$0, 3, 3, \cdots$	DES

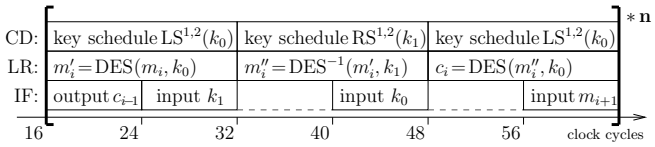

Figure 6. Register contents when the pipeline is configured for 3DES encipherments with two keys k_0 and k_1, possibly chained $i \in [0:n[$ times (in which case the indicated clock cycles must be added $i \times 48$.)

In the case of 3DES with two keys (k_0 and k_1, $k_2 = k_0$), it is noticeable that the computation never stalls. As a matter of fact, the key for the first of the three DES is already present in CD, since the last the key was $k_2 = k_0$. Consequently a new message m_i can be loaded instead, and the next computation can follow seamlessly.

3.3. SW/HW Trade-offs

The proposed pipelined architecture of Fig. 5 is versatile, since all modes of operation can be fit. Nevertheless, this architecture suffers three drawbacks, discussed in the following three paragraphs.

Realization of 3DES with three different keys.
In 3DES with three keys, it would be necessary to load the first key k_0 and the new message block m_i at the same time. However, the RAM delivering the data is single-port and there is a single IR register. As there is a contention, the two loadings must be done sequentially. As CD has can kept a key globally unchanged during 8 clock cycles, it is loaded first. During the extra eight clock cycles required to load m_i, the pipeline stalls, because it is starving data. Triple-DES with three keys can thus be used with modes of operation, but it is the only exception where the cipherments do not chain gracefully.

Realization of CBC^{-1}.
As already indicated in Tab. 2, CBC cannot be deciphered directly. The reason is that to retrieve plaintext block m_i, the following XOR must be computed: $m_i = \text{DES}^{-1}(c_i) \oplus c_{i-1}$. Unfortunately, the XOR right-hand side c_{i-1} has already been consumed by the pipeline (to compute $\text{DES}^{-1}(c_{i-1})$) when it is needed again. Re-fetching the ciphertext c_{i-1} in memory would require to freeze the pipeline during 8 clocks cycles, which is not desirable.

The first workaround is to implement CBC^{-1} by EBC^{-1}, which yields m_0, $m_0 \oplus m_1$, $m_1 \oplus m_2$, *etc.* instead of m_0, m_1, m_2, *etc.* The processor can afterwards compute (in software) the XOR between the couples in the memory ram[0:N[to retrieve the correct plaintext. An example programme is listed below:

```
register char tmp0, tmp1;
for( register char i=0; i<8; ++i ) {
  tmp0=ram[i]; // The 1st block is only read
  for( register size_t j=1; j<N; ++j ) {
    tmp1=ram[j*8+i];      // Read  jth block
    ram[j*8+i]=tmp0^tmp1; // Write jth block
    tmp0=tmp1;
  }
}
```

The second workaround we propose is the smartest, because it does not require any post-processing in software. The idea is to adapt the control to decipher the blocks c_i in reverse order. If we note $c'_i \doteq c_{N-1-i}$, then $m_i = \text{DES}^{-1}(c'_{i-1}) \oplus c'_i$, for $i \in]N:0]$, is computable by the multi-mode architecture of Fig. 5. It is the same configuration as CFB^{-1}, but with the key schedule set to decipher.

Using CBC and CBC^{-1} with an IV.
At last, CBC and CBC^{-1} modes cannot be used with an IV. The IV should indeed by loaded, kept in some register (say LR) while the first block m_0 is built-up into IF, The computation could then start with the first operand IV$\oplus m_0$. However, this scenario also implies that LR has an enable, which we explicitly want to avoid.

A first solution relies on the software. The task simply consists in XORing the first block prior to calling an encipherment or after a decipherment.

A second solution consists in adding an initialization procedure, where $\text{DES}^{\pm 1}(\text{IV})$ is first computed. Then, every message to cipher is simply prepended $\text{DES}^{\pm 1}(\text{IV})$. For long messages, this overhead in processing time becomes negligible.

A third solution imply to increase the DES engine area. The datapath is augmented with an 8-bit XOR operator that would compute "input $\oplus$ output" (with the notations of Fig. 5.) This result would be injected into the multiplexor in front of the IF register. It is a design choice to decide whether it is worth implementing this minor hardware feature that complexifies both the datapath and the control (since the IF multiplexor has a new input).

4. Performance Evaluation of the Proposed Architecture

The three architectures discussed in this paper, namely the "straightforward" (Fig. 1), "pipelined" (Fig. 3) and "multi-mode" (Fig. 5) have been synthesized in a "low-leakage" 130 nm technology. The synthesis results, for both the control and the datapath, are given in Fig. 7. The

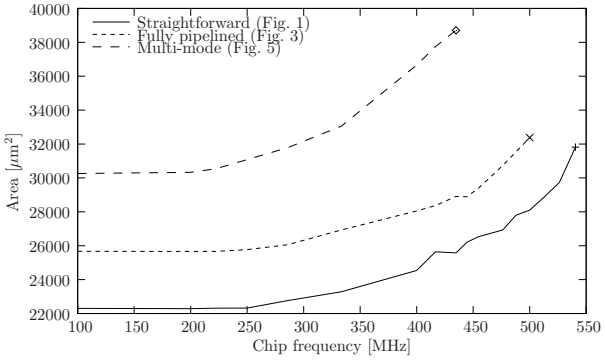

Figure 7. Synthesis results for the three architectures.

straightforward architecture is the most compact and the multi-mode is the largest. The designs maximum frequency are 540 MHz (straightforward DES), 500 MHz (pipelined DES), 435 MHz (multi-mode DES.) The pipelined DES does not reach the same frequency as the straightforward DES because its more complex control limits its speed. The multi-mode DES datapath is more sophisticated, which explains why it cannot reach frequencies as high as the two other architectures. The maximum frequency of the proposed architectures are fairly high for an embedded system. The architectures can be adapted to an external datapath width of $n = 16$ (resp. $n = 32$) bits, in which case two (resp. four) rounds can be computed within one clock period. This new architecture will run at a maximum speed roughly half (resp. four times less.)

However, the cipherment throughput is the highest for the pipelined architecture in ECB mode, and for the multi-mode in all the other modes and triple DES. Table 3 shows the throughput of some modes. It should be noted that neither the straightforward nor the pipelined architectures are designed to handle modes of operation or triple-DES. The chaining operation must thus artificially performed in SW. An estimation of the code for such an operation is given below:

1. Read `ram[i]` *(1 clock cycle)*
2. Read `ram[i+8]` *(1 clock cycle)*
3. Compute `ram[i] XOR ram[i+8]` *(1 clock cycle)*
4. Write `ram[i+8]` *(1 clock cycle)*

This fragment must be repeated 8 times, which leads to a total of $8 \times 4 = 32$ clock cycles. This evaluation is optimistic, because it does not take into account the context switch. It is also unrealistic, since the processor should not be disturbed by the computation internal details. The throughput figures given for straightforward or the pipelined are thus only indicative.

Table 3. Throughput of some modes of the three studied implementations of DES.

	Straightforward	Pipelined	Multi-mode
DES-ECB	2.000	4.000	4.000
DES-CBC	1.000	1.000	4.000
3DES-ECB	0.571	0.571	1.333
3DES-CBC	0.444	0.444	1.333

The maximum throughputs are also shown graphically in Fig. 8 (a) for DES-ECB and in Fig. 8 (b) for 3DES-CBC. It is also interesting to compare the throughputs of an ASIC design with the one of a personal computer (PC.) The maximum throughput for 3DES-CBC attained by the multi-mode architecture is 580 Mbit/s, while a 3.2 GHz PC is only able to encrypt at 200 Mbit/s (result of `openssl speed des`.)

However, achieving high throughput would be needless if the area overhead is getting too large. The instantiation of multiple engines could thus multiply the throughput at the same cost. Therefore, in Fig. 9, the throughput divided by the area is plot. At constant area, the multi-mode architecture of DES remains the fastest.

The DES module after automatic place-and-route is shown in Fig. 10. It happens that the synthesizer was optimistic: static timing analysis performed on the final layout at 95% placement density reports a maximal frequency of 286 MHz (*versus* 435 predicted by the logical synthesizer.) This limitation is in practice not deterrent, since 256 bytes embedded RAMs in 130 nm technology cannot work above 333 Mhz without violating either hold or setup times.

5. Conclusion

Two architectural innovations, namely the I/O and processing pipelining and the use of "IP representation", allow to improve the design of DES 8-bit implementations. The proposed architecture supports all modes of operation and triple DES with two keys. The hardware implementation can take advantage of both methods, whereas software implementations can only benefit from the "IP representation". The pipelining strategy consist in parallelizing the data inputs and outputs with the processing. It also enables shorter clock periods, due to the elimination of the some multiplexors on the critical path. The IP representation enables optimized chaining. These optimizations allow to accelerate DES operations in smartcards or in embedded systems or to speed-up DES-cracking machines.

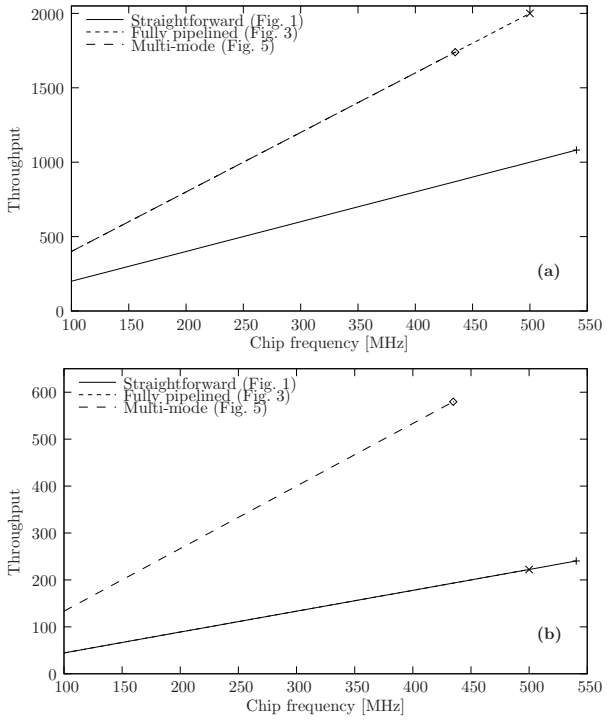

Figure 8. Throughput (in 10^6 bit/s) of the three solutions in (a) DES-ECB and (b) 3DES-CBC.

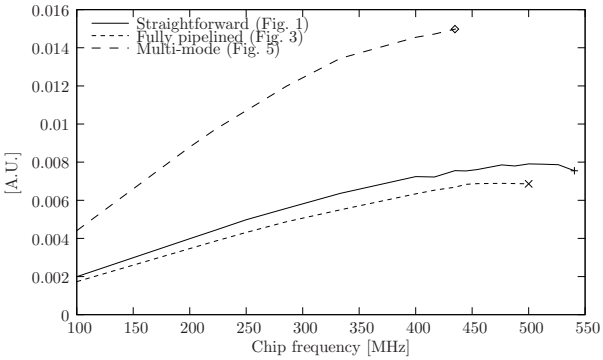

Figure 9. Comparative efficiency of 3DES-CBC (in Mbit/s/μm^2) for the three proposed architectures.

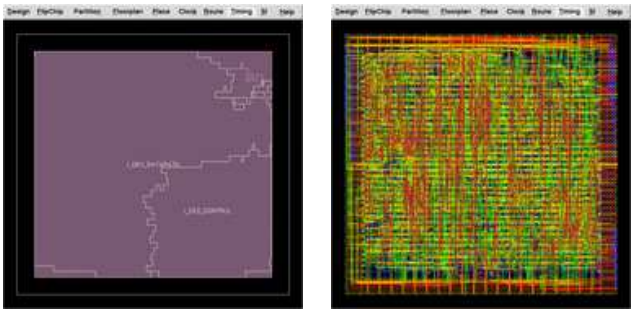

Figure 10. The multi-mode DES after place-and-run in 130 nm technology. *Left*: Datapath / Control partitioning; *Right*: Final layout.

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